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SELECTION OF ALUMINUM ALLOYS FOR U.S. ARMY VEHICLES USING MULTI-ATTRIBUTE UTILITY ANALYSIS

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MATERIALS PRODUCIBILITY BRANCH

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ABSTRACT

A new generation of aluminum alloys is being developed with properties superior to current alloys. In order to assess which alloys are of primary interest for a given application, a multi-attribute utility analysis (MAUA) was performed over the range of properties expected. Three decision makers were surveyed to quantify their preferences toward various alloy characteristics.

After quantifying the decision maker's preferences, it was determined that a new aluminum alloy, 2519-T87 (conforming to MIL-A-46192) shows great promise for replacing the currently used 5083-H131 (conforming to MIL-A-46027) and 7039-T67 (conforming to MIL-A-46063).

This work is a preliminary assessment to MAUA as a decision aid in the selection of materials for use in new Army vehicles. This technique can effectively assess the relative desirability of materials with different characteristics, however certain anomalies must be accounted for. The present work examined the generic desirability of certain alloy properties to provide a fundamental understanding of the basic method to others who may be able to apply this decision analysis tool to their own specific applications. Future research will apply this decision making technique to more focused applications, but will expand the choice of materials to include other metals, ceramics, polymers, and their composites. (Readers who are more concerned with the results of this study than the theory behind it should consult Table 2 in the Results section for the alloy properties, Figures 6-10 in Appendix I for the individual utility profiles, and Table 3 in the Results section of the text.)

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Definition of Symbols

Symbol	Meaning
A,B	generic attributes
,	max or min
a,b	constants
p	preference or probability of
U	utility of
K	single attribute scaling factor
$\mathbb{K}$	multi-attribute scaling factor
x_i	i^{th} of a set of n attributes
Π_i	multiplicative operator *for a series of i terms*

INTRODUCTION

The purpose of this research program was to quantitatively rank current and newly developed aluminum alloys for potential use in Army applications. This difficult problem is important to address as the number of alternative alloy systems available to the designer is growing at a rapid rate. Additionally, if this technique can successfully evaluate aluminum alloys, then the technique can potentially decide between alternative materials such as plastics and ceramics as well as metals.

Multi-attribute utility analysis (MAUA) assesses the value of a material for a particular application on the basis of its performance, cost, safety, and other factors. Also, this technique qualifies and quantifies the relative importance of various performance characteristics. This allows alloy researchers to concentrate on developing the properties which are important to the end user.

The concept of "utility" was invented in order to rank the worth of various events (or attributes) on a single scale. This allows material properties such as strength, cost, and weight (which have very different units of measure) to be ranked on a single scale.

A simplified example of the concept of utility could be the amount of pleasure (utility) a person derived from consuming hot dogs. If consuming 1 hot dog gives the person 1 unit of pleasure, a hungry person may derive 2 units of pleasure from eating 2 hot dogs. Eating 8 hot dogs, however, is unlikely to provide 8 units of pleasure. The person may prefer to consume a soft drink to get his third unit of pleasure rather than consume additional hot dogs. Similarly, for an Army armor application, a decision maker may insist on a certain amount of ballistic protection. Increases above this amount may be considered unnecessary and the decision maker may then prefer lower weight or cost. The desirability of a set of potential occurrences will depend on certain aspects of the decision maker's situation. Such aspects may include financial resources, needs, and attitudes towards risk.

The assessment of the utility of a particular attribute (a property of the material) is performed by asking the decision maker to chose between a known level of performance and a chance of getting either better or worse performance. The decision maker is asked to quantify the probability (p), or known level (A), where he or she is indifferent to the lottery in Figure 1.
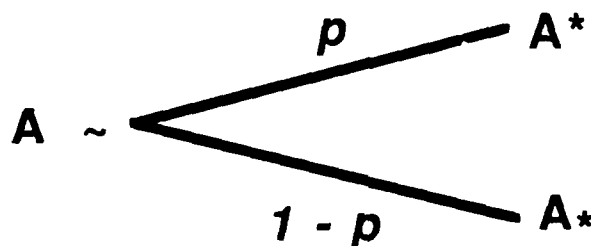

Figure 1. The Basic Preference Lottery

For example, if A* is $1, and A* is $0, and p is 0.5, the expected value (A) of the lottery is 50 cents and a person may actually trade the lottery for 50 cents. If the person is risk averse, he may trade the lottery for only 40 cents. As the stakes grow larger, people usually become more risk averse. Thus, if a coin toss is worth $100,000, a person may well trade the lottery for a sure $5,000 (well below the expected value of $50,000).

Assessing the utility function of the decision maker in the previous example, a utility of 1 is assigned to the best outcome (receiving $100,000), and a utility value of 0 is assigned to the worst outcome (receiving nothing). The utility value (U) of receiving $5,000 is defined as:

$$U(A) = p(U(A^*)) + (1-p)(U(A_*)) \qquad (1)$$

For the previous example this equation would read: the utility associated with $5,000 equals 0.5 (the probability of getting heads) times the utility associated with getting $100,000 (which we have defined to be equal to 1) plus 0.5 times the utility associated with getting nothing (which we have defined as 0). Thus, the utility of getting $5,000 equals 0.5. If the decision maker wanted $15,000 for the lottery, then the utility of getting $15,000 would be 0.5. Thus the utility of an attribute corresponds to the price of a lottery ticket or the premium on an insurance policy.

Another method of determining the utility function, especially when non-linear attributes are being considered, is to ask the decision maker to determine the probability where he or she is indifferent to a lottery. Taking the previous example, one would ask the decision maker to determine the probability(p), where he or she is indifferent to the lottery in Figure 2.
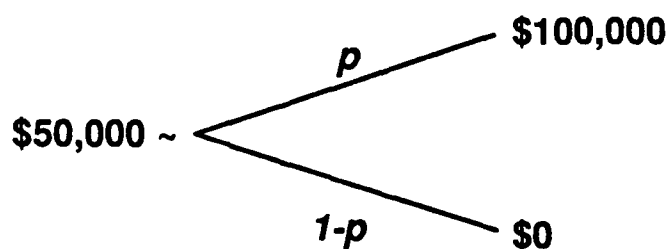

Figure 2. Determining the Indifference Level

Since we have defined the utilities of the best and worst attributes as equal to 1 and 0, the utility of $50,000 equals the probability, p, chosen because the second term in Equation 1 becomes zero. If the decision maker is fairly consistent, he or she may choose a probability of 0.8 which would result in the utility function shown in Figure 3. (Note that for the above example the decision maker is risk averse; thus his utility lies well above the expected value shown as a dashed line in that Figure.) A utility function need not be completely assessed in order to obtain useful information. Often, the answers

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to only one or two lotteries can give enough information to discern general trends and make decisions. Utility functions are only valid for the range of attributes studied. In this case, if the utility associated with $200,000 is desired, a new set of questions must be asked.
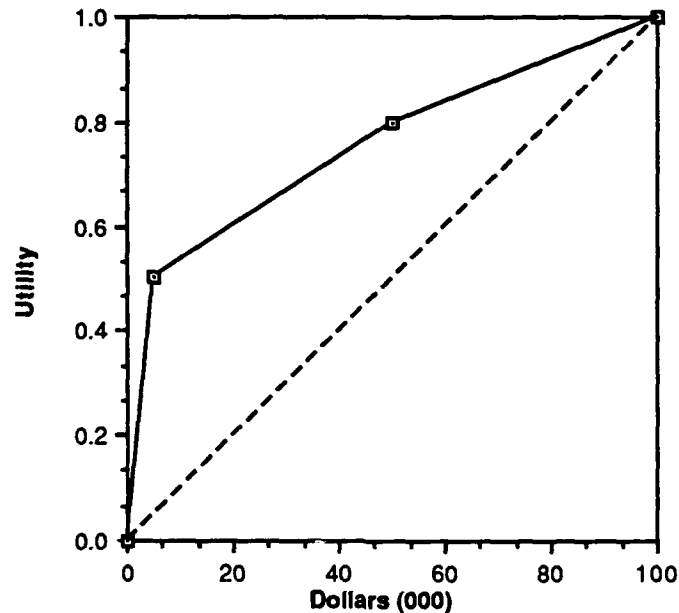

Figure 3. Example Utility Function

If a number of different attributes are to be assessed, the utility function of each attribute is determined separately (on a scale of 0 to 1). Then each utility function is rescaled to reflect how importantly that attribute is valued with respect to the other attributes. This simultaneous valuation of different attributes is the core of MAUA.

Consider an analysis concerning two attributes. The utility function of each attribute is determined separately on a scale of 0 to 1. The utility of the worst value of attribute A, $U(A_*)$, equals zero, and the utility of the best value of attribute A, $U(A^*)$, equals one. Similarly, the utilities associated with the worst and best value of attribute B go from zero to one: $U(B_*) = 0$, $U(B^*) = 1$. In order to assess the utility associated with some combination of these two attributes, the overall utility will be scaled from 0 to 1 and each of the separate (or single dimension) attributes need to be rescaled. In this case, $U(A_*,B_*) = 0$ and $U(A^*,B^*) = 1$. Referring to Figure 4, we know the shape of the utility curve on the ordinate and abscissa (from the single dimension utility functions A and B), and we know that two of the corner points are 0 and 1 (marked on the Figure). The remaining information needed to completely define the two dimension utility function is the shape of the upper and right axes and the value of the other two corner points $U(A_*,B^*)$ and $U(A^*,B_*)$. By

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invoking the concept of "utility independence", we assume that a given utility function's shape will remain constant while other attributes vary. Thus, the utility function of A when $U(B) = 1$ can be represented by a positive linear transformation of the same utility function for A when $U(B) = 0$ (i.e. $U(A)_{B^*} = aU(A)_{B_*} + b$). The value of the corner points are determined by asking the lotteries shown in Figure 5.
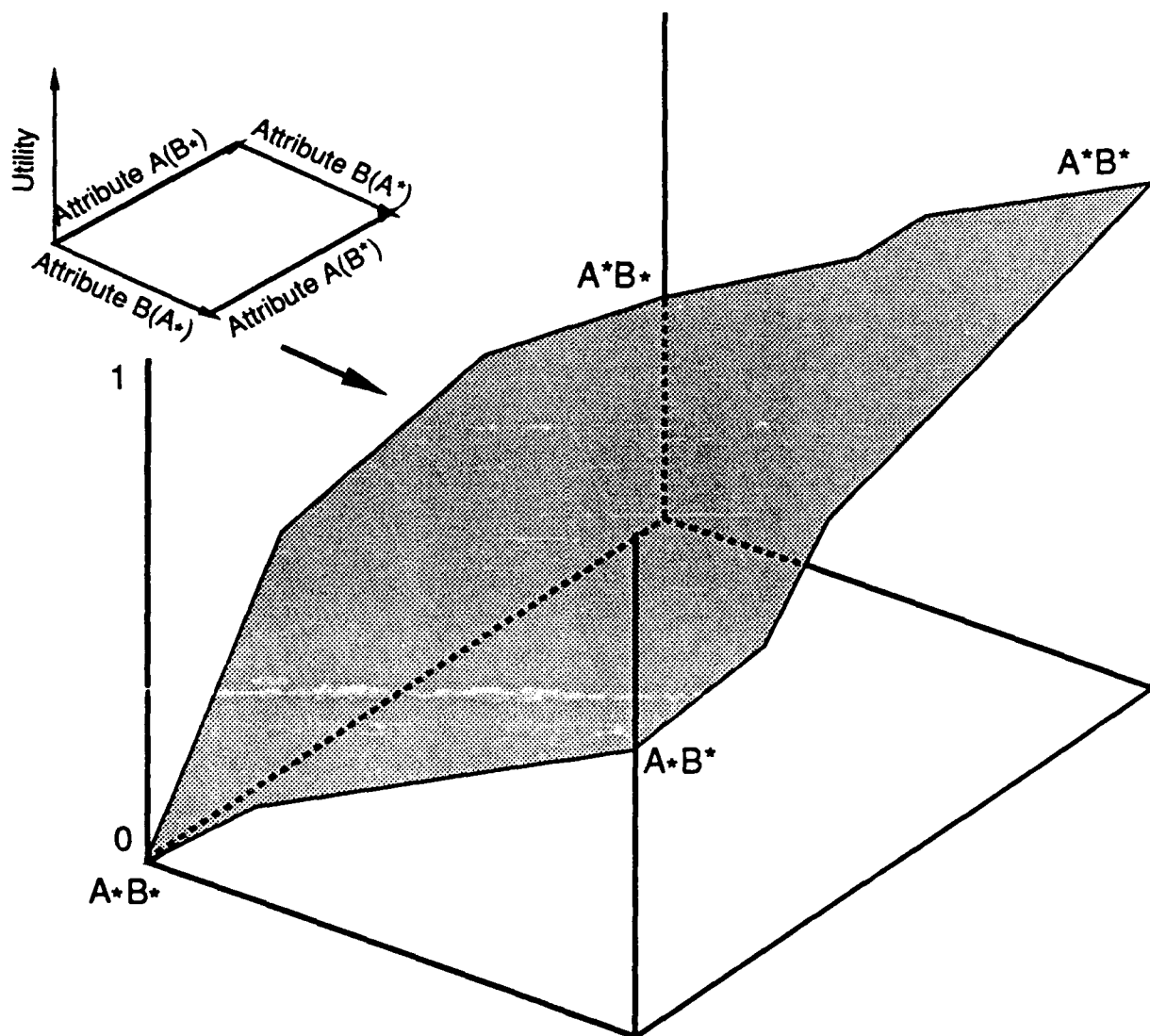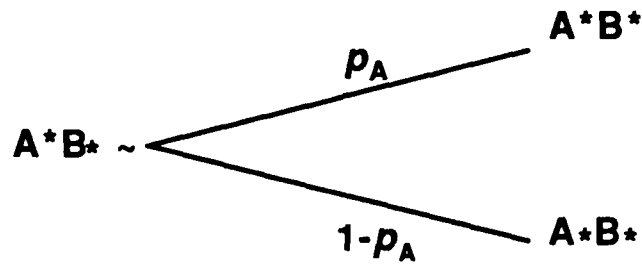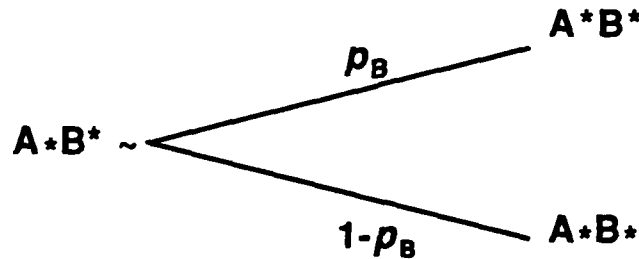

Figure 4. Generic Two Dimension Utility

and

Figure 5. Preference Tests for a Two-Dimension Utility

The utility of any given set of attributes within the chosen range can now be determined. (A generic two-dimension utility function is shown in Figure 4.) In general, for n attributes, the following equation can be used to determine the overall utility:

$$\mathbb{K}U(x) + 1 = \prod_i (\mathbb{K}K_i U_i(x_i) + 1) \tag{2}$$

where $U(x)$ is the overall utility for some combination of attributes, x_i. K_i is a "ceiling factor" (the corner point associated with that attribute), and $U_i(x_i)$ is the utility associated with a single attribute. We determine all of the $U_i(x)_i$ and K_i are from the survey, then $\mathbb{K}$ (the global scaling factor) can be found by solving this equation for x_i^* which has a utility, $U(x) = 1$. In general the survey is constructed so that K_i equals the probability chosen in the survey question concerning that attribute.

In the previous example, we would determine $\mathbb{K}$ by inputting the proper values for the upper right point from Figure 2 into Equation 2, yielding:

$$\mathbb{K}(1) + 1 = \{\mathbb{K}(0.7)(1) + 1\}\{\mathbb{K}(0.5)(1) + 1\} \tag{3}$$

Once $\mathbb{K}$ is solved, we can determine the utility associated with any set of attributes within the range studied.

By asking a series of these types of questions, the relative importance of an attribute is determined. If the decision maker will trade off one attribute for the chance of gaining a large value in a different attribute, then the decision maker's preferences can be assessed. A more detailed account of utility assessment and MAUA can be found in the work of de Neufville (1) or Fields (2).

EXPERIMENTAL PROCEDURE

There are four basic steps in assessing the utility associated with performance characteristics of a material. The range of properties being analyzed is determined, and a utility is assigned to the best and worst case (usually 1 and 0, respectively). Next, the single attribute utility functions are determined. After the relative utility of each dimension (single attribute) is caculated, the single attribute utility functions are rescaled so that the overall utility will go from 0 for the worst combination of material characteristics to 1 for the best combination. Once the multi-attribute utility function is defined, the utility of each material is determined.

The performance characteristics used for the initial analysis included: yield strength, ductility, cost, density, ballistic performance, and corrosion resistance. The range of these characteristics studied was chosen to be broad enough to include the performance of 5083-H131, 7039-T67, 2519-T87, and a newly developed Rapidly Solidified Powder (RSP) aluminum alloy. The values of the materials performance characteristics are shown in Table 1. A survey to quantify these characteristics was developed with the aid of decision analysis experts from the Massachusetts Institute of Technology (3,4). Example questions from this survey are included in Appendix 3 (Paragraph 3 in the Discussion section addresses some of their problems.)

Table 1. Aluminum Alloy Properties

	5083	7039	2519	RSP	units
Cost	1.60	2.00	2.00	4.00	$/lb
Density	2.66	2.81	2.81	2.40	gm/cc
Ballistics	1800	2160	2160	2160	fps*
Corrosion	2000	100	3000	3000	hrs (to crack)
Strength	46.2	58.0	61.4	80	ksi (yield)
Ductility	9.3	13.6	12.4	15	%

$*V_{50}$ = velocity in feet per second (fps) that will penetrate
the target 50% of the time

Three decision makers were surveyed from the U.S. Army Materials Technology Laboratory: the Chief of the Processing Technology Division, the Chief of the Armor Materials Division, and an expert in ballistic materials. Decision makers were asked to comment on the range and type of attributes being analyzed. Their initial answers were confirmed with personal interviews. In actual procurement of Army vehicles, none of these three people make the final decision. However, their opinions are based on experience with what has been procured. Also, since this was a preliminary assessment of the use of this technique, surveying the actual decision makers was not felt to be appropriate at the present time.

RESULTS

The preferences of the armor experts were not adequately assessed with this survey. Although they were very candid with their answers and comments, their scope of concern was artificially constrained. To them, the most important attribute was ballistic performance on an equivalent weight basis. They declined comment on the issue of cost. All other characteristics were seen to be only as important as their effect on ballistic performance. For example, the armor experts did not evaluate strength except for the anticipated effect on ballistic performance.

Most of the armor experts' single dimension utility functions were binary. Corrosion resistance had to be above a certain level, and any further increases were considered completely irrelevant. The same was true of strength and ductility except for the potential of affecting ballistic performance.

However, the armor experts did point out that the survey's characterization of ballistic performance was insufficient. Armor design must consider many elements. What threat (fragmentation simulators, armor piercing, heat round)? What obliquity (angle of penetration)? What thickness of material? What degree of spalling? Different areas of the vehicle are designed to defeat different ballistic threats. Thus, the material and its thickness may vary considerably depending on its location on the vehicle. Quantifying ballistic protection alone would require another MAUA. Therefore, it was decided that this utility analysis would concentrate on selecting the material used for the underlying structure of a vehicle rather than attempt to understand which armor system to use for a particular location on a vehicle.

The person responsible for processing technology was able to quantify his preferences toward material attributes other than ballistics. He was concerned with the overall properties of the material for the entire structure rather than the specific shell around it. His preferences were based on the desire for balanced performance rather than the concentrated development of a single characteristic. For this reason, it was decided to analyze only his results in this study.

The initial survey went smoothly with the exception of a few minor difficulties (see paragraph 3 in the Discussion section). The single attribute functions fell within the accepted profiles. However after completing the

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questions to determine the interactive scaling, it was evident that something was amiss. Calculation of the overall utilities in Table 2 confirmed this:

Table 2. Utilities from First Round Survey

Alloy	5083-H131	2519-T87	RSP	7039-T64
Utility	0.995	0.998	0.999	<0.982

The corrosion resistance of the 7039 was actually not good enough to be within the range studied. However, substituting the baseline value (2000 hrs) made the utility of 7039 comparable to the others.

It is evident that the results are so close to each other as to be virtually meaningless. Also, all of the results are too close to the top end of the scale (~0.99 on a 0 to 1 scale). This result was completely unexpected, and is not mentioned in the theory of multi-attribute utility analysis.

In order to understand why the results of this particular analysis were so unsatisfactory, the overall utilities were redetermined using a wide variety of fictitious survey answers. It was found that as the number of K_i terms with values close to 1 increased, the value of K became closer to -1. This in turn makes the overall utility approach 1, thus decreasing the resolution or sensitivity of distinguishing between the utility of various alloys. Thus, if the decision maker considers every attribute to be very important, the analysis will be unable to distinguish between the candidate materials.

In response to this, a new two-step survey was developed. This survey has a wider range, fewer attributes, and more questions. This allowed each single attribute utility function to be better assessed. Next, the functions determined to be binary were eliminated from the final determination of the K_i (corner points). (A binary function attribute is one that must be above a certain level or else that material would not be used. Below a certain threshold value, the single dimension utility is close to zero, and above the threshold, it is close to one.)

The newly developed survey is attached as Appendix 4. (Although density was eliminated in the new survey, ballistic performance was modified to be ballistic performance on an equivalent weight basis.) The single attribute utility functions resulting from this survey of the processing technology decision maker are shown in Figures 6-10. As can be seen, the stress corrosion cracking and ballistic performance attributes are binary functions. This simply means that the decision maker is averse to risking a decrease in the current level of these properties. His attitude was much more flexible concerning cost, strength, and density. (*The actual values used in the figures and the decision maker's responses to the survey and the subsequent interview are confidential. However, the reader may gain a more complete understanding of the development of utility curves by consulting the example in Appendix IV.*)

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First, the scaling of the single attribute utility functions was determined with questions 6-8 in the survey. These answers determine the corner points of the multi-attribute utility function. Next, the attributes of 5083, 7039, and the RSP aluminum (shown in Table 1, Appendix 2) were used to determine the overall utility associated with each material. The stress corrosion and ballistic performance characteristics were checked to make sure they are above the binary threshold values shown in Figures 7 and 9; 7039 possessed inferior stress corrosion cracking properties and was eliminated. The values for the RSP aluminum were estimated from research conducted by Pickens, et al. (5). The RSP values used were the best possible within the range studied except for the cost which was the worst within the range. (This reflects the expected profile of a developmental material.)

For the remaining three materials, K was calculated to be -0.586. The resulting utilities are listed in Table 3. This result appears to have much better resolution than the previous attempt. The 2519 and 5083 have comparable utilities, but the RSP is clearly less. The 7039 would not be chosen due to its low stress corrosion cracking resistance.

Table 3. Utilities from Revised Survey

Alloy	5083-H131	2519-T87	RSP
Utility	0.923	0.934	0.376

DISCUSSION

This preliminary analysis has demonstrated the potential application of multi-attribute utility analysis for selecting aluminum alloys. It has also demonstrated the drawbacks associated with this technique. If too many attributes are being assessed simultaneously, the sensitivity can be significantly reduced. Also, the use of binary functions can help identify anomalous results. For example, a material may have a number of great properties, but one property may be low enough to disqualify the material. The overall utility of this alloy may be high, but by using a binary function one can decide that it is nonetheless unsatisfactory.

Among the aluminum alloys studied in this report, 2519-T87 was found to demonstrate the most desirable set of attributes. It should be noted though, that the results presented here were based on a single person's response. The inclusion of additional responses could change these results significantly. However, the technique of multi-attribute utility analysis does show promise as a method of assessing performance differences between alternative materials.

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Another problem with the first survey was that some of the questions were unintentionally deceptive. For example, initially one may assume that more is better. However, less weight and less cost are more desirable. Another deceptive point was asking to judge between getting double or one-half performance. The initial impulse is to believe that the known performance is midway between these two extremes rather than actually one-third of the way between them. (The use of simple lotteries in the second version of the survey eliminated the ambiguity of this question. The actual values are used rather than subjective terms such as one-half or double.) These adjustments to the survey were made during the personal interview which followed the survey. This revision underscores the importance of interviewing the decision maker. It is likely that the interview is the most crucial aspect of the analysis, as has been suggested by Clark (3).

Two of the underlying assumptions in multi attribute utility analysis, utility independence and preferential independence, were never explicitly validated. However, since all of the materials studied were of a similar class of materials (aluminum), it is felt that these assumptions are valid. If a number of different classes of materials are to be studied (ceramics, metals, polymers) then a number of questions must be added to the survey to validate these assumptions.

The quantification of ballistic performance is a difficult issue. Protection versus armor piercing projectiles was chosen for this survey, but future surveys will need to examine a variety of threats. Another question which was raised concerned weldability, which is an extremely difficult attribute to quantify. Perhaps weldability rating on a scale of 1 to 10 can be derived (via a MAUA) from the materials welding requirements and welded properties. *(The importance of this attribute has since been demonstrated in ballistic tests where the welded 2519 failed at much lower values than the base alloy.)*

This survey assessed the generic desirability of a material since specific design requirements for a particular application were not available. (Such detailed information would have made it easier for the decision maker to answer the survey. However, this does not detract from the overall objective of this study.) The greatest asset of this technique may be to provide a better understanding of the specific needs for a given application. Accordingly, this technique is best used as a preliminary decision aid and not as a final design arbiter. This publication described one general use of this technique which can be modified for other specific Army uses.

Other new materials such as the metal matrix composites can be assessed using MAUA in the future. Based on the present analysis, major emphasis should be placed on lowering the cost of new candidate materials for armor applications. Other attributes may not be important enough to override prohibitively high costs. However, for components that require high specific stiffness, a MAUA may show that cost is not the controlling attribute.

CONCLUSIONS

Multi-attribute utility analysis was demonstrated to be useful for evaluating aluminum alloys for Army applications. This technique can potentially be expanded to include alternative materials such as plastics, composites, and ceramics. However, this technique must be used with caution in order to obtain accurate results.

The preliminary assessment in this report is that 2519-T87 (conforming to MIL-A-46192) is a candidate material for replacing 5083-H131 and 7039-T67 in Army vehicles.

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3) J. Clark, Professor of Materials Engineering, Massachusetts Institute of Technology, personal communication, April, 1987.

4) F. R. Fields, III, Massachusetts Institute of Technology, personal communication, April, 1987.

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APPENDIX I
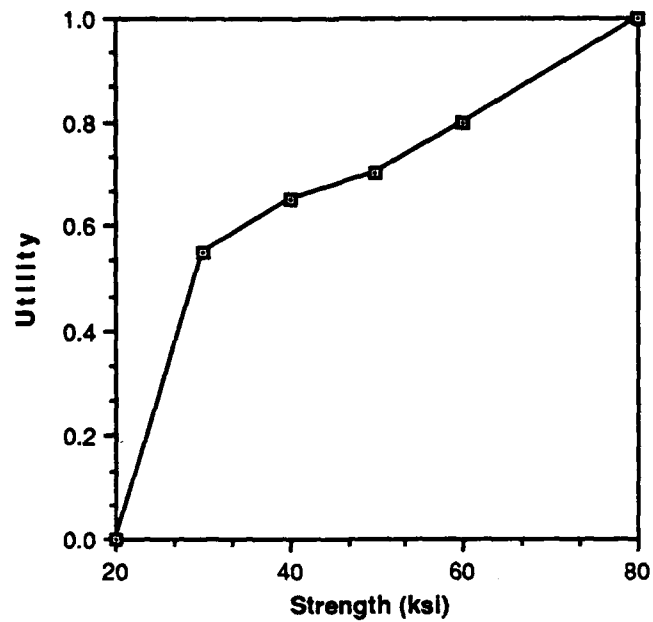
Figure 1-6. Utility of Yield Strength
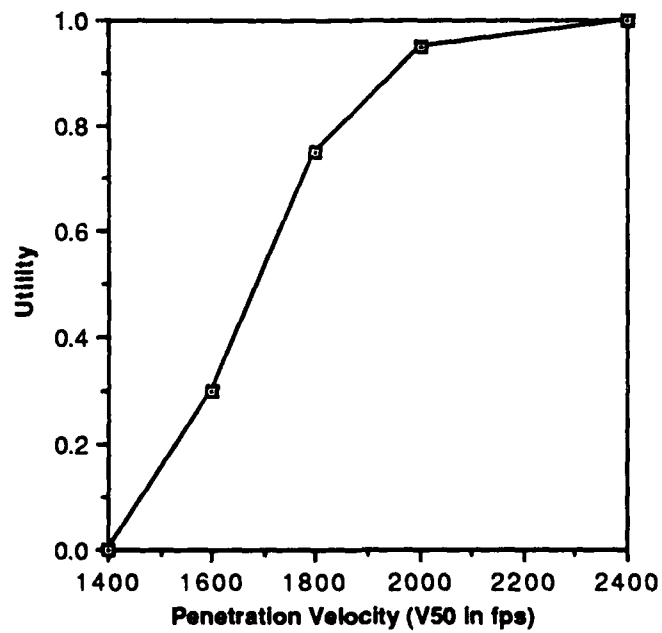
Figure 1-7. Utility of Ballistic Protection
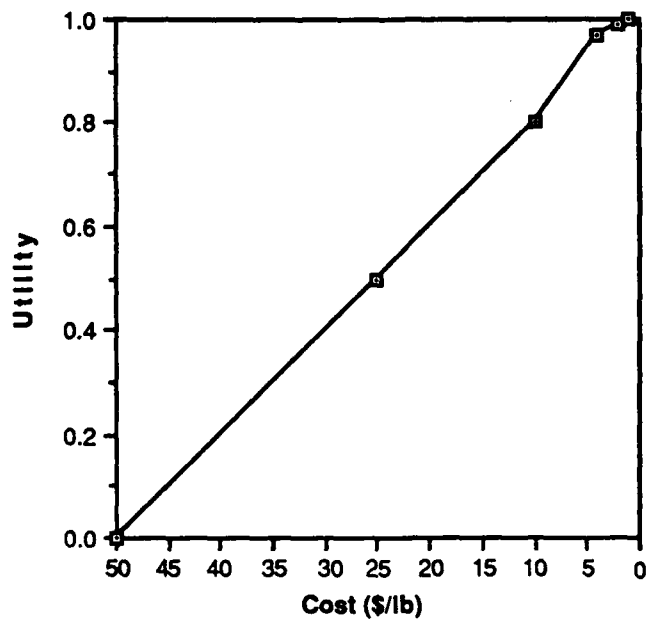
Figure 1-8. Utility of Alloy Cost
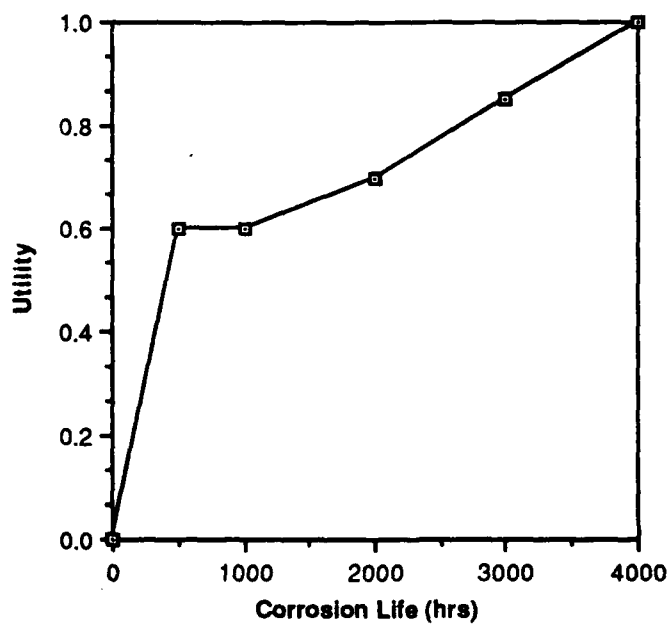
Figure 1-9. Utility of Corrosion Life

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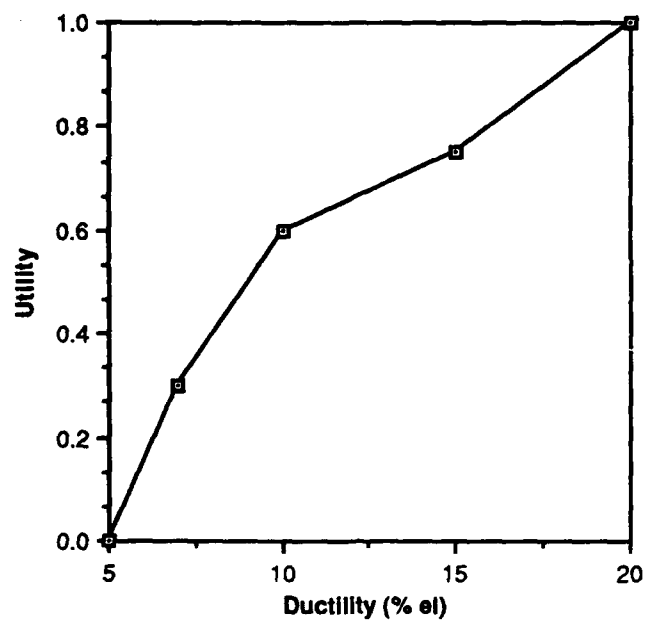
Figure 1-10. Utility of Ductility

APPENDIX II

Question 1

Suppose that a new aluminum alloy is available whose performance is identical to the old aluminum alloy except for its strength. Due to variability in the production of aluminum plate from one producer to another, the new aluminum will exhibit variations in strength. A test performed on 10 plates show that p percent have greater strength (80 ksi), but the other 100 - p percent have lower strength (20 ksi). The present alloy always exhibits 40 ksi yield strength.

Would you prefer the new material to the old if the probability p were:

p	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Yes											
No											

Questions 7 through 13

In order to describe the test results of a new series of aluminum armor alloys, your engineers have devised a hypothetical "perfect alloy". All alloys are then compared to this perfect alloy and are ranked between it and a "least case" alloy. In general, your engineers have found that all of the materials end up being equivalent to the "least case" in all respects except for one characteristic which is equal to the "perfect alloy". In order for them to rank these alloys quantitatively in their scale from best to worst, you are presented with a series of lotteries. Each lottery allows you to chose between the given new alloy and a percent chance P of getting the perfect alloy or (1 - p) chance of getting the worst case alloy.

"Perfect Alloy"

Cost	25 % less
Weight	20 % less
Ballistics	20 % better
Corrosion	twice tme
Strength	twice yield
Ductility	twice el %

"Test Alloy"

Cost	25 % less
Weight	20 % lmore
Ballistics	20 % worse
Corrosion	one-half time
Strength	one-half yield
Ductility	one-half el %

p

1 - p

"Worst Alloy"

Cost	twice as much
Weight	20 % more
Ballistics	20 % worse
Corrosion	one-half time
Strength	one-half yield
Ductility	one-half el %

p	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Yes											
No											

APPENDIX III

ALUMINUM ARMOR SELECTION

INTRODUCTION

This questionnaire is designed to obtain an understanding of your preferences toward various characteristics of materials. It will be used as a preliminary exploration of the factors leading to the selection of a material for Army fighting vehicle applications. The results will be used to complement the Army Materials Technology Laboratory's research programs on existing and newly emerging materials.

This questionnaire is designed to provide data for a multi-attribute utility analysis. This is the second version of this survey, using improvements suggested by decision makers such as yourself. We are aware that this questionnaire is still limited in several ways and thus will be followed up by an interview. Please feel free to comment and advise us of any apparent limitations.

The questions were formulated to help us understand your expert professional judgement. As such, there are no right or wrong answers. Rather, through your answers to these questions, we hope to understand how you trade off different characteristics (strength, cost, or ballistic performance) of materials.

Before we begin asking questions about how you trade off various characteristics, we need to define the operating range of the characteristics being studied. In the table below, we have identified what we feel are representative values of five characteristics. We have also determined maximum and minimum values for each characteristic. Please examine this list and make any corrections or changes which you feel are applicable.

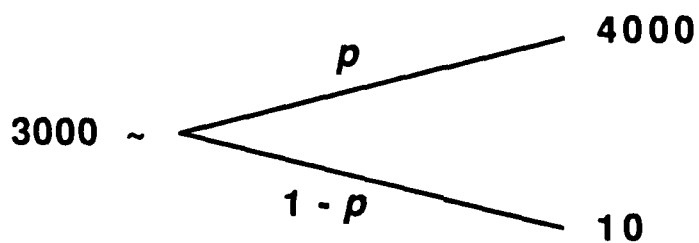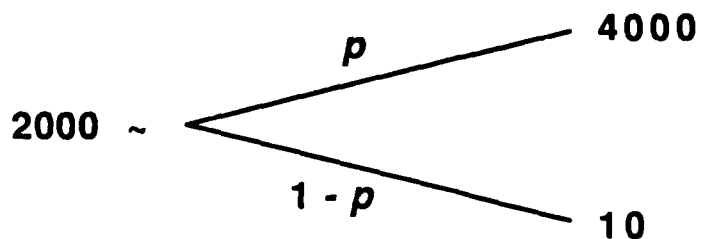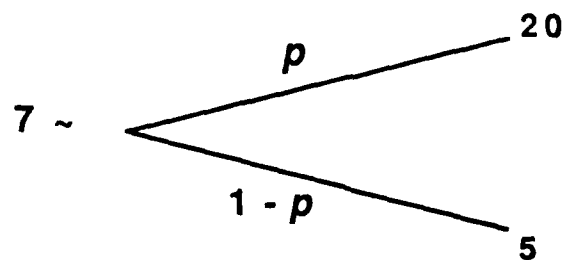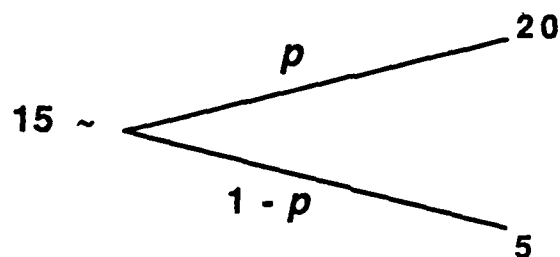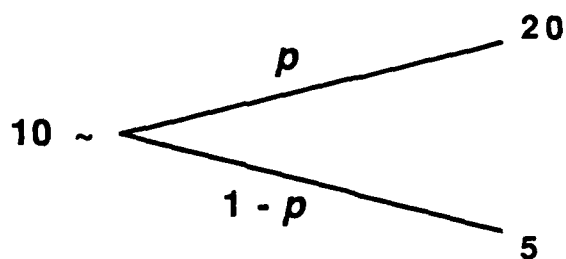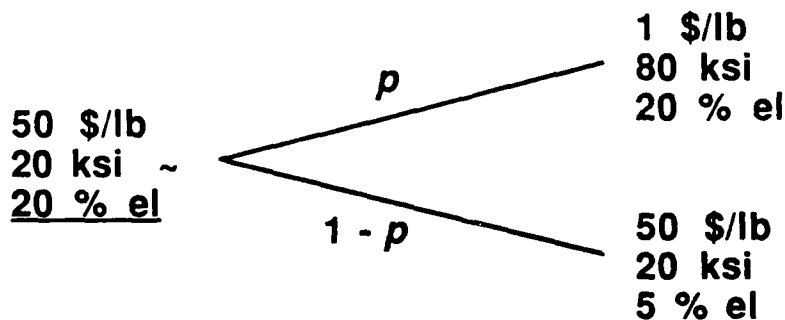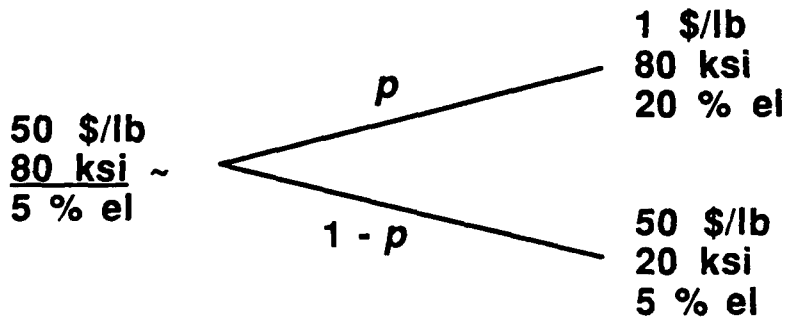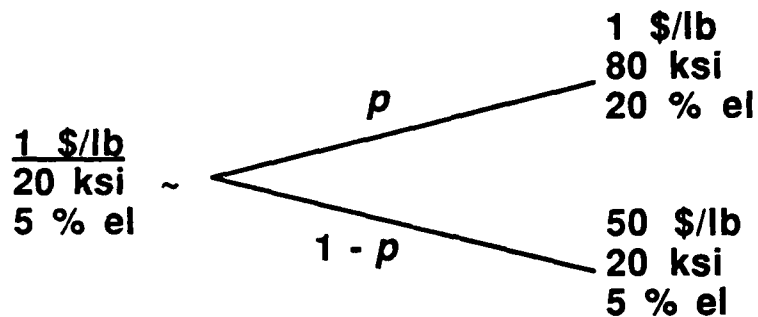| Characteristic	How Measured	Max.	Min.
Cost	dollars (/lb)	4	1
Ballistics	Penetration velocity (fps)	2200	1400
Corrosion	Cracking time (hrs)	4000	10
Strength	Yield (ksi)	80	20
Ductility	elongation (%)	20	5

Question 1

In each of the following lotteries what probability (p) of success would you require to trade the given level of strength for the best possible level of strength?

$$40 \sim \begin{cases} p & \longrightarrow 80 \\ 1-p & \longrightarrow 20 \end{cases}$$

$$30 \sim \begin{cases} p & \longrightarrow 80 \\ 1-p & \longrightarrow 20 \end{cases}$$

$$60 \sim \begin{cases} p & \longrightarrow 80 \\ 1-p & \longrightarrow 20 \end{cases}$$

$$50 \sim \begin{cases} p & \longrightarrow 80 \\ 1-p & \longrightarrow 20 \end{cases}$$
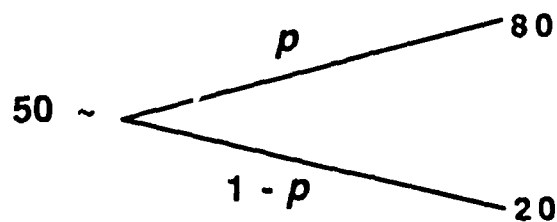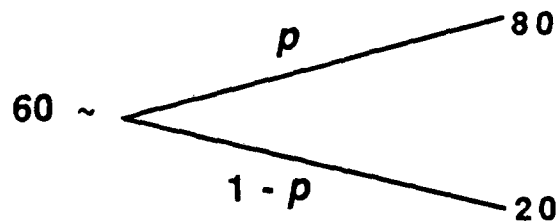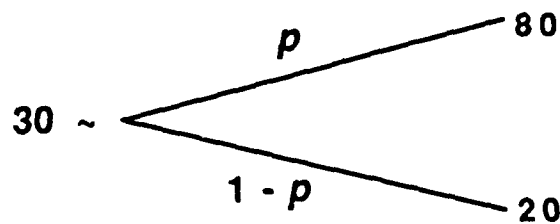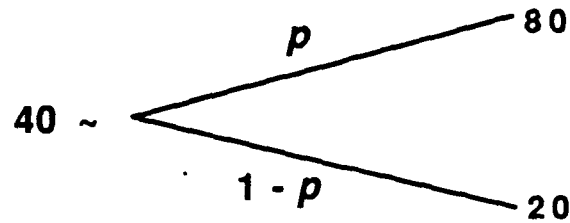
Question 2

Ballistic Protection (fps)

In each of the following lotteries what probability (p) of success would you require to trade the given level of ballistic protection for the best possible level of ballistic protection?
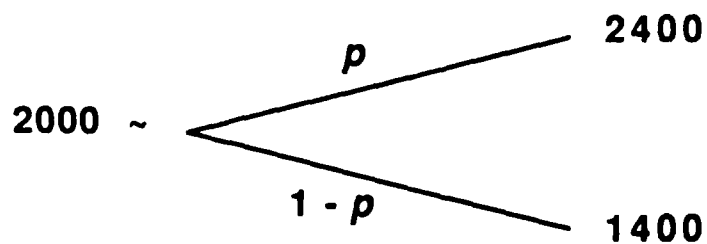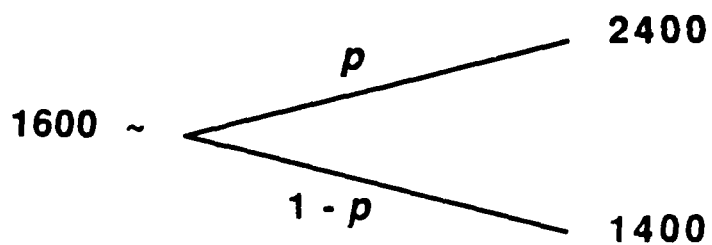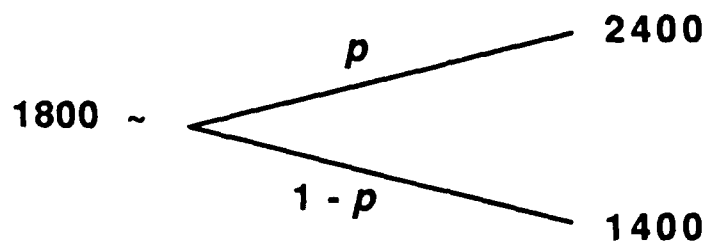
$$1800 \sim \begin{cases} \xrightarrow{\ p\ } 2400 \\ \xrightarrow{1-p} 1400 \end{cases}$$

$$1600 \sim \begin{cases} \xrightarrow{\ p\ } 2400 \\ \xrightarrow{1-p} 1400 \end{cases}$$

$$2000 \sim \begin{cases} \xrightarrow{\ p\ } 2400 \\ \xrightarrow{1-p} 1400 \end{cases}$$

Question 3

In each of the following lotteries what probability (**p**) of success would you require to trade the given cost for the best possible cost?

$$25 \sim \left\langle \begin{array}{l} \overset{p}{} \quad 1 \\ \underset{1-p}{} \quad 50 \end{array} \right.$$

$$10 \sim \left\langle \begin{array}{l} \overset{p}{} \quad 1 \\ \underset{1-p}{} \quad 50 \end{array} \right.$$

$$2 \sim \left\langle \begin{array}{l} \overset{p}{} \quad 1 \\ \underset{1-p}{} \quad 50 \end{array} \right.$$

$$2 \sim \left\langle \begin{array}{l} \overset{p}{} \quad 1 \\ \underset{1-p}{} \quad 4 \end{array} \right.$$
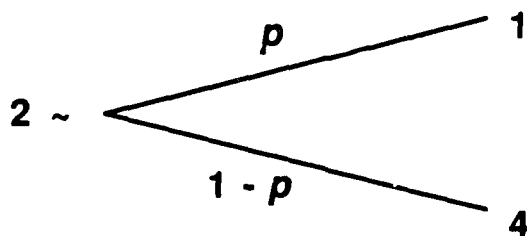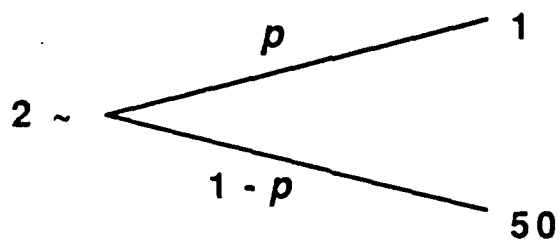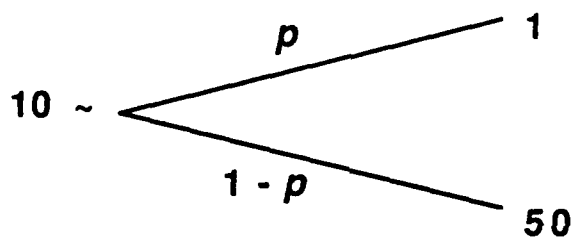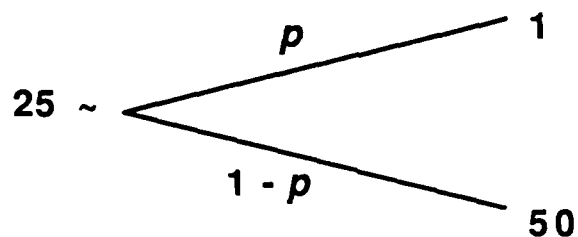
Question 4

<u>Corrosion Life (hrs)</u>

In each of the following lotteries what probability (*p*) of success would you require to trade the given corrosion life for the best possible corrosion life?

2000 ~ [*p* → 4000 ; 1 - *p* → 10]

3000 ~ [*p* → 4000 ; 1 - *p* → 10]

1000 ~ [*p* → 4000 ; 1 - *p* → 10]

500 ~ [*p* → 2000 ; 1 - *p* → 10]
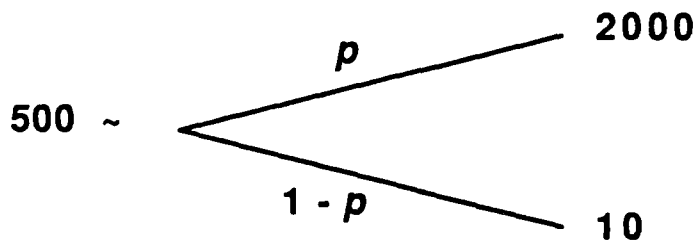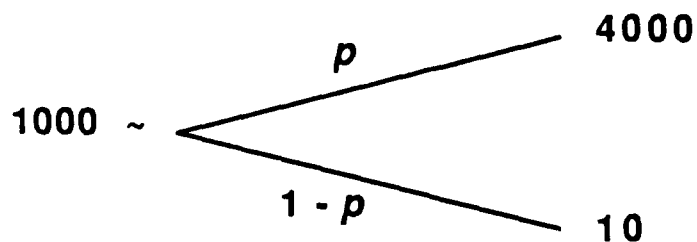
Question 5

Ductility (% el)

In each of the following lotteries what probability (p) of success would you require to trade the given level of ductility for the best possible level of ductility?

```
              p          20
        ┌─────────────
10 ~ ───┤
        └─────────────
            1 - p        5
```

```
              p          20
        ┌─────────────
15 ~ ───┤
        └─────────────
            1 - p        5
```

```
              p          20
        ┌─────────────
7 ~ ────┤
        └─────────────
            1 - p        5
```

Questions 6-8

Interactive Attribute Scaling

In each of the lotteries below, the alloy in question shares one attribute with the "ultimate alloy" and two attributes with the "worst alloy". In each case, determine the probability (p) of success you would require to risk your alloy to obtain the ultimate alloy.

<u>1 $/lb</u>
20 ksi ~
5 % el

       p

1 $/lb
80 ksi
20 % el

       $1 - p$

50 $/lb
20 ksi
5 % el

50 $/lb
<u>80 ksi</u> ~
5 % el

       p

1 $/lb
80 ksi
20 % el

       $1 - p$

50 $/lb
20 ksi
5 % el

50 $/lb
20 ksi ~
<u>20 % el</u>

       p

1 $/lb
80 ksi
20 % el

       $1 - p$

50 $/lb
20 ksi
5 % el

APPENDIX IV

Example Development of a Utility Function

A certain vehicle component is being considered for a materials substitution. The 2 key design criteria are strength (A) and cost (B). The design limits specify a minimum strength of 75 ksi and a maximum cost of $225. Material I, currently used, has a strength of 90 ksi and costs $180. Material II, which is being developed, has the potential for a strength of 95 ksi (A*) and a cost of $155 (B*). However, there is a chance it will only produce a strength of 80 ksi (A*) and a cost of $205 (B*). The project manager for the component is asked (briefly) what odds of delivering the best properties would he require of Material II before substituting it for Material I. Presented with the following preference lotteries, the decision maker selects the probabilities shown below.

Single Dimension Utilities

Assign $U(X_I{}^*) = 1$ and $U(X_{I*}) = 0$

25
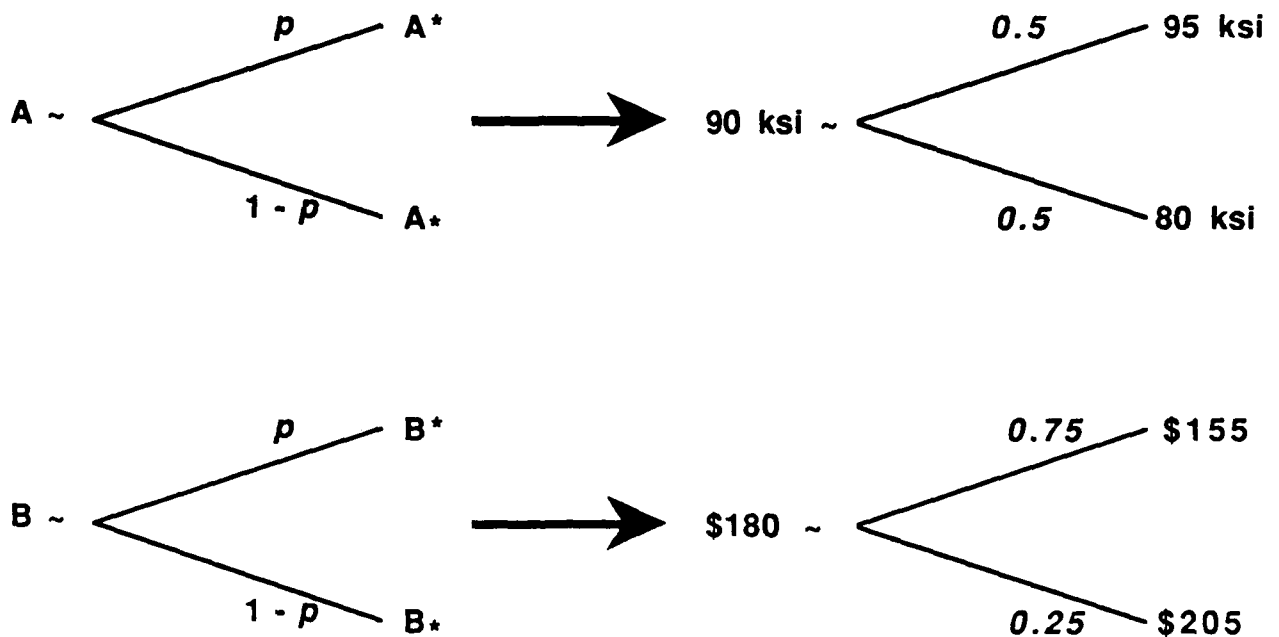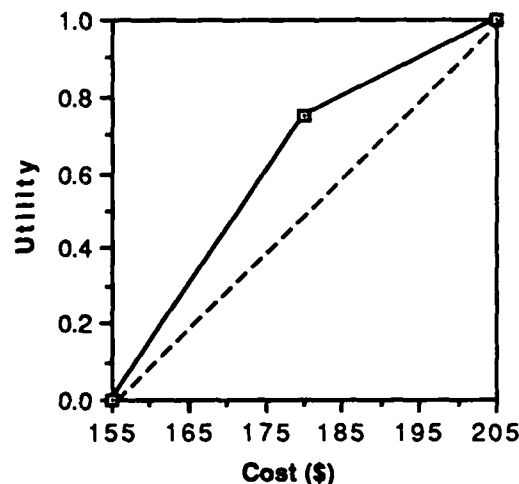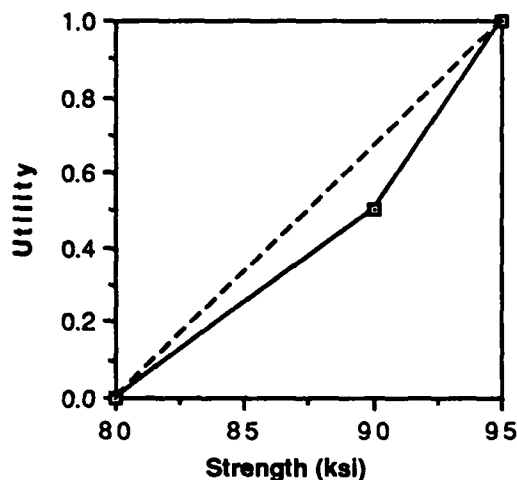
Applying Eqn. 1:

$$U(A) = pU(A^*) + (1 - p)U(A_*)$$
$$= 0.5(1) + (0.5)(0) = 0.5$$

$$U(B) = pU(B^*) + (1 - p)U(B_*)$$
$$= 0.75(1) + (0.25)(0) = 0.75$$

     Thus, the individual utility of each attribute for this decision maker has been approximated. Apparently, cost is more of an issue within the stated limits. (note from the shape of the utility functions that the designer is risk averse with cost, but not with strength.) To develop the MAUA for this example, we must determine the interaction between the attributes - the so-called "corner points" of two dimensional function. Again, in passing, we ask our decision maker the odds he would require to trade a compromise material for the best possible material (given that he may receive the worst).
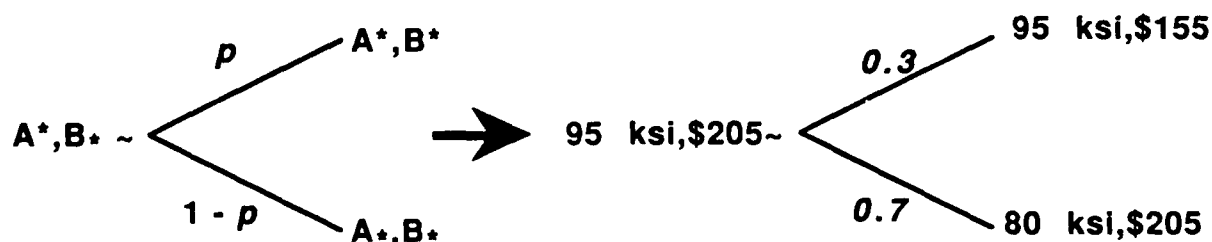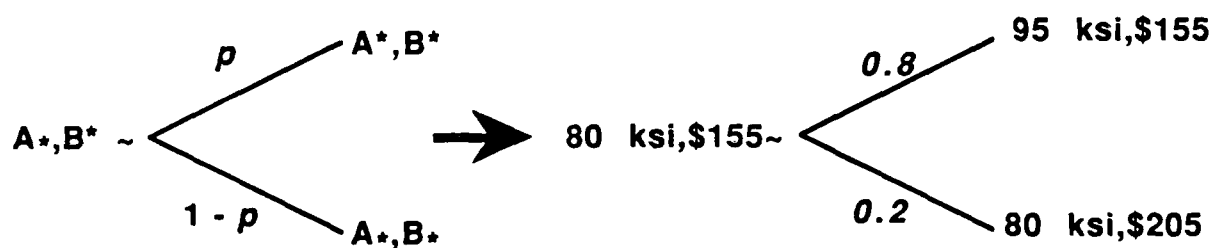
Again we assign a utility of 1 to the best case and a utility of 0 to the worst case. Performing calculations similar to the single dimension case, we find

$$K_{ksi} = 0.3 \quad \text{and} \quad K_{\$} = 0.8$$

These values are the scaling factors representing the utility interdependence of the attributes. The scaling factors allow us to calculate the normalizing factor (K) for the composite function using Eqn. 3 as follows:

$$KU(X_i) + 1 = \prod_i (KK_iU(X_i) + 1)$$

For two attributes this reduces algebraically to

$$KU(X_i) + 1 = (KK_AU(A) + 1)(KK_BU(B) + 1)$$

Because of how we proposed our questions, this equation can be further simplified by solving for X_i^*, which requires $U(X_i^*) = 1$ and

$$K(1) + 1 = (KK_{ksi}(1) + 1)(KK_{\$}(1) + 1)$$

$$\downarrow$$

$$K = \frac{1 - k_{ksi} - k_{\$}}{k_{ksi}\, k_{\$}}$$

Plugging in the values of our scaling factors gives

$$K = \frac{1 - 0.3 - 0.8}{0.3(0.8)} \approx -0.42$$

Now we can calculate the utility for any known combination of attributes within the ranges evaluated. For example, material I produced a component with 90 ksi strength costing \$180. Using Eqn. 2:

$$KU(I) + 1 = (KK_{ksi}U(ksi) + 1)(KK_{\$}U(\$) + 1)$$

$$\downarrow$$

$$U(I) = KK_{ksi}U(ksi)K_{\$}U(\$) + K_{ksi}U(ksi) + K_{\$}U(\$)$$

$$= (-0.42)0.3(0.5)0.8(0.75) + 0.3(0.5) + 0.8(0.75)$$

$$= -0.04 + 0.15 + 0.60 = \mathbf{0.71}$$

Let's suppose that material II actually was developed and yielded 80 ksi at a cost of $155. Following the same calculation:

$$U(II) = (-0.42)0.3(0)0.8(1) + 0.3(0) + 0.8(1)$$

$$= -0 + 0 + 0.8 = 0.8$$

On the basis of the calculated utilities, we can recommend to our decision maker that material II should be developed to replace material I on the basis of his own preferences.

N.B. The attribute values chosen for material II were well defined points from the single dimension utility functions. The utility for other values (within the given limits) could be derive by linear interpolation on the original utility functions. Better results would be obtained by adding more data points (i.e. asking more questions).

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USING MULTI-ATTRIBUTE UTILITY ANALYSIS - Steven A. Gedeon
and Charles T. Lane

Technical Report MTL TR 89-1, January 1989, 30 pp -
illus-tables, AMCMS Code 612105.H84

A new generation of aluminum alloys is being developed with properties superior to current
alloys. In order to assess which alloys are of primary interest for a given application, a
multi-attribute utility analysis (MAUA) was performed over the range of properties expected.
Three decision makers were surveyed to quantify their preferences toward various alloy char-
acteristics. After quantifying the decision maker's preferences, it was determined that a
aluminum alloy, 2519-T87 (conforming to MIL-A-46192) shows great promise for replacing the
currently used 5083-H131 (conforming to MIL-A-46027) and 7039-T67 (conforming to MIL-A-46063).
This work is a preliminary assessment of MAUA as a decision aid in the selection of materials
for use in new Army vehicles. This technique can effectively assess the relative desirability
of materials with different characteristics, however certain anomalies must be accounted for.
The present work examined the generic desirability of certain alloy properties to provide a
fundamental understanding of the basic method to others who may be able to apply this decision
analysis tool to their own specific applications. Future research will apply this decision
making technique to more focused applications, but will expand the choice of materials to in-
clude other metals, ceramics, polymers, and their composites. (Readers who are more concerned
with the results of this study than the theory behind it should consult Table 2 in the Results
section for the alloy properties, Figures 6-10 in Appendix I for the individual utility pro-
files, and Table 3 in the Results section of the text.)